USGS Landslide Hazard Maps for Seattle, Washington

INTRODUCTION

Landslides, particularly debris flows, have long been a significant cause of damage and destruction to people and property in the Puget Sound region. Following the landslide events of 1996 and 1997, the Federal Emergency Management Agency (FEMA) designated Seattle as a "Project Impact" city with the goal of encouraging the city to become more disaster resistant to the effects of landslides and other natural hazards. A major recommendation of the Project Impact council was that the city and the U.S. Geological Survey (USGS) collaborate to produce a landslide hazard map of the city. An historical data set archived by the city and compiled into digital form by Shannon and Wilson, Inc., contains more than 100 years of landslide data from severe storm events. This database allowed comparison of actual landslide locations with those predicted by modeling and analysis. As a result, we were able to produce a suite of four types of landslide maps for Seattle: (1) a shallow-landslide hazard map, (2) a landslide-terrain map, (3) a landslide recurrence and probability map, (4) hazard map for deep landslides, and (5) a prototype landslide hazard map linked to rainfall intensity.

Shallow Landslide Hazard Map

The "Shallow Landslide Hazard Map" (a portion shown in figure 1) portrays the susceptibility and relative hazard of Seattle slopes to shallow landslides, the most common type of rainfall-induced slope failure that occurs in Seattle. They are particularly hazardous to people and property because they often transform into debris flows, water-laden slurries of soil and weathered bedrock that can travel rapidly (35–40 mph) downslope. The stability of each slope segment in the map area was indexed, and the results were compared with the landslide data set. The resulting map indicates categories of relative landslide hazard for the entire city of Seattle (fig. 1). This map

will allow Seattle city officials and planners to make more informed future decisions regarding areas of shallow-landslide hazard within the city.

Landslide Terrain Map using LIDAR Imagery

The "Landslide Terrain Map" (fig.2) shows the geomorphology of the Seattle area with respect to three landslide features—landslide headscarps, landslide deposits, and denuded slopes (slopes formed by mass wasting and erosion since retreat of glacial ice). This mapping effort involved the use of Light Distance and Ranging (LIDAR) data to expose landslide morphology in the many heavily vegetated areas in Seattle. Shaded relief, slope, and topographic contour maps derived from the LIDAR data were used to create the map. Nearly all of the landslides mapped from this data are complexes consisting of numerous individual landslides (fig. 3). Mapped landslides, headscarps, and denuded slopes delineate areas of historical landslide activity more thoroughly than previous Seattle-wide landslide mapping efforts. Over 93% of more than 1,300 reported historical landslides occurred within the boundaries of the LIDAR-mapped landforms. Virtually all (99.7%) natural historical landslides occurred within these boundaries.

Map of Landslide Probability and Recurrence

The "Landslide Probability and Recurrence Map" (fig. 3) indicates annual landslide probabilities for the city of Seattle. The historical landslide database compiled by Shannon & Wilson, Inc., for the City of Seattle was used to apply a time-dependent probabilistic approach to the evaluation of future landslide occurrence in Seattle. The database contains a record of landslides that occurred during the period 1909 to 1999. It includes records of the location and timing of about 1,300 landslides; geologic setting, dimensions, style of failure, and the apparent influence of drainage modification or slope engineering. Landslides reported in the database are primarily those that caused damage to
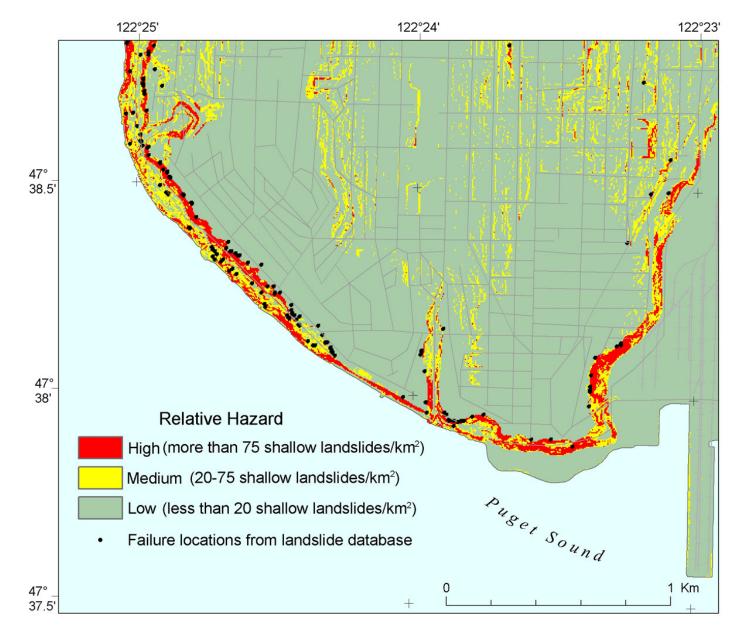
Figure 1. Shallow-landslide hazard map, showing the southwest portion of the Magnolia area of Seattle.

private property or infrastructure, and in general the accuracy and completeness of the record increases with recency. Landslide density contours were established using the landslide database as input to probability models. Results from these models show that about 9% of the area of Seattle has annual exceedance probabilities of 1% or greater. Maximum annual exceedance probability of future occurrence of individual landslides has a value of 25% on a hillslope in West Seattle (fig. 5). Maximum annual exceedance probability of future occurrence of a year with one or more landslides is 17%, based on application of the models.

Deep Landslide Hazards

Deep landslides on the coastal bluffs of Puget Sound can cause extensive property damage. These slides are typically triggered by groundwater conditions resulting from extended wet winters rather than individual storms. Because they are large, their stability is controlled by three-dimensional (3-D) effects, including complex 3-D groundwater flow as well as 3-D variations in strength and topography. The "Deep Landslide Hazard Map" (fig. 4) indicates the potential for these large landslides by showing the relative stability and instability of slopes on the bluffs of southwestern Seattle.
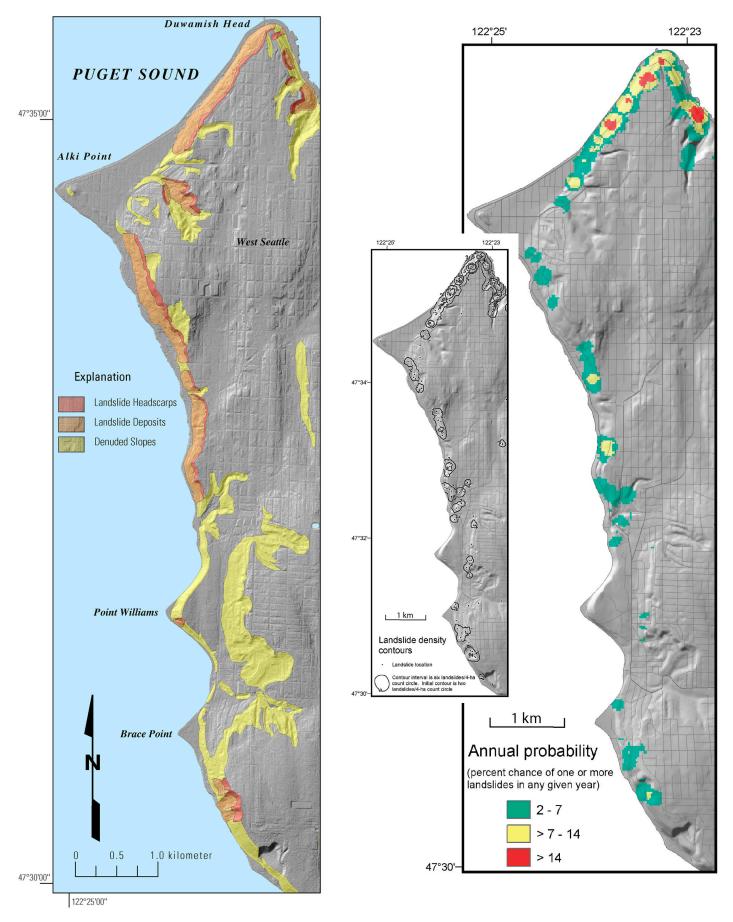
Figure 2. Landslide terrain map, showing the West Seattle area.

Figure 3. Landslide probability and recurrence map, showing the West Seattle area. Inset shows landslide-density contours that were used to create the map.
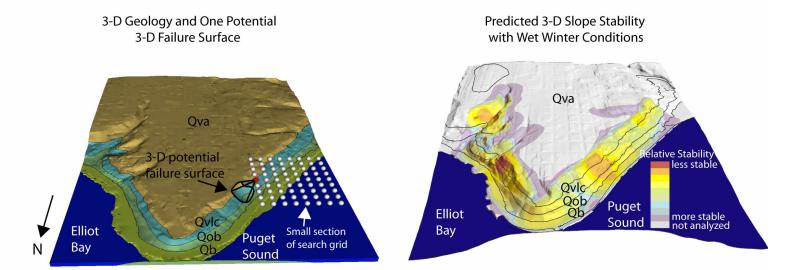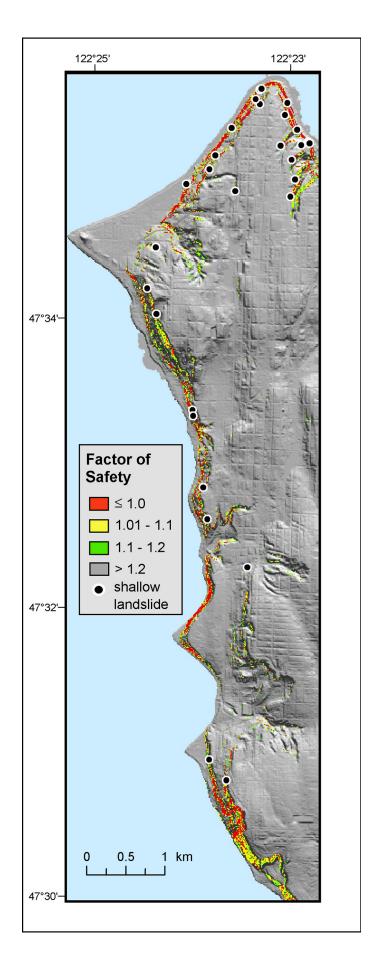
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Figure 4. Deep landslide model and hazard map for the Duwamish Head area of Seattle.

This map was created using USGS models for analyzing 3-D groundwater flow and 3-D slope stability combined with recent geologic mapping and high-resolution topography. The results demonstrate that when slopes are dry, steepness and strength control potential instability. However, where groundwater perches on lower permeability clay layers, extended wet winter conditions can increase the water table near the bluff. Elevated groundwater pressures can lower slope stability. Given extended wet conditions, our 3-D analyses identify lower stability areas in and adjacent to historically active deep-seated landslides.

Prototype Maps Linked to Rainfall

To continue to improve the state-of-the-art in mapping landslide hazards, we have also developed a prototype dynamic method to map landslide susceptibility as rainfall occurs. Our methods for mapping landslide hazard zones begin with field studies and physically based models to assess relative slope stability, including the effects of material properties, seasonal groundwater levels, and rainfall infiltration. These new tools allow us to model landslide hazard using actual or forecast rainfall information and to depict the changes in slope stability as they evolve during a storm (fig. 5). This will allow us to provide more accurate landslide warnings and alerts to aid the mitigation of landslide hazards.

Figure 5. Prototype landslide-susceptibility map linked to 28 hours of rainfall from the January 18–19, 1986, storm.

Map legend:

Factor of Safety
- ≤ 1.0
- 1.01 - 1.1
- 1.1 - 1.2
- \> 1.2
- ● shallow landslide

0   0.5   1 km

For more information concerning these maps see:

http://landslides.usgs.gov

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